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Multispectral imaging for predicting firmness and soluble solids content of apple fruit

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Abstract

Firmness and soluble solids content (SSC) are important quality attributes for apples and many other fresh fruits. This research investigated the feasibility of using multispectral imaging to quantify light backscattering profiles from apple fruit for predicting firmness and SSC. Spectral images of the backscattering of light at the fruit surface, which were generated from a focused broadband beam, were obtained from Red Delicious apples for five selected spectral bands (10 nm bandpass) between 680 and 1060 nm. Ratios of scattering profiles for different spectral bands were used as inputs to a backpropagation neural network with one hidden layer to predict fruit firmness and SSC. The three ratio combinations with four wavelengths (680, 880, 905, and 940 nm) gave the best predictions of fruit firmness, with $r = 0.87$ and the standard error of prediction (SEP) = 5.8 N. Only two ratios with three wavelengths of 880, 905 and 940 nm were needed for predicting the SSC of apples with $r = 0.77$ and SEP = 0.78%. The multispectral imaging technique is promising for predicting firmness and sweetness of apples.

Keywords: Fruit; Apple; Firmness; Near-infrared; Scattering; Imaging; Neural networks

1. Introduction

Firmness and sugar content are important quality attributes that directly influence consumers on purchasing fresh apple fruit. Nondestructive sensing of fruit for internal quality, especially firmness and sugar content, would allow the fruit industry to provide better, more consistent fruit to the consumer and, thus, improve industry competitiveness and profitability.

Abundant literature exists on nondestructive sensing techniques for determining fruit firmness (Abbott et al., 1997). Past research was largely focused on using mechanical methods, such as quasi-static compression, vibration, impact, and sonic or ultrasonic, to measure fruit firmness. While many of these mechanical techniques have shown potential for measuring firmness, they have not been adopted in commercial packing facilities for sorting apple fruit either because they still cannot meet the firmness grading requirements or they are too difficult to implement, or too slow, for online sorting applications.

Considerable recent research activities have been reported on using near-infrared spectroscopy (NIRS) for determining internal quality, especially the soluble

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solids content (SSC, or total sugar content), of apples and other fresh fruits (Choi et al., 1997; Dull et al., 1989; Kawano et al., 1992; Lu, 2001; Lu et al., 2000; Lammertyn et al., 1998; Moons et al., 1997; Slaughter, 1995). Commercial developments and applications of NIRS instruments and equipment for nondestructively measuring and/or sorting fruit for SSC have been reported recently (Kawano et al., 1994; Temma et al., 2002). NIRS has also been studied for predicting the firmness of apples and other fruits (Choi et al., 1997; Lu, 2001; Lu et al., 2000; McGlone and Kawano, 1998; Moons et al., 1997). Although a general trend of correlation exists between NIRS measurements and fruit firmness, the technique still cannot predict fruit firmness accurately and reliably.

The unsatisfactory performance of NIRS for predicting fruit firmness may be explained from its measurement principle. When a light beam hits the fruit, a small fraction is reflected at the surface (specular reflectance) and the rest will penetrate into fruit tissue. Upon entering the fruit tissue, photons scatter in different directions for various times before being absorbed or exiting from the fruit at various distances from the incident point (this reflected light is called diffuse reflectance). Absorption and scattering are two basic phenomena as light interacts with biological materials. Light absorption is related to certain chemical constituents in the fruit, such as sugar, acid, water, etc. (Williams and Norris, 2001). On the other hand, scattering is a physical phenomenon that is dependent on the density, cell structures, and extra- and intra-cellular matrices of fruit tissue. Hence, light scattering is expected to be useful for quantifying certain mechanical and/or textural properties of fruit such as firmness. Modern reflectance NIRS measures an aggregate amount of light reflected from a sample, from which light absorption may be estimated and then related to certain chemical constituents such as sugar, acid, etc. However, NIRS does not provide quantitative information on light scattering in the sample. Hence, its capability for predicting structurally related properties, such as fruit firmness, is limited or difficult to justify.

Birth and colleagues (Birth, 1978, 1986; Birth et al., 1978) explored the potential of using light scattering to sense agricultural products. They used a transmission technique to quantify light scattering in food samples. Birth et al. (1978) reported that light scattering is useful for predicting the physical properties of agricultural products, such as pale, soft, and exudative (PSE) in pork. However, the transmission technique is difficult to implement, and often impractical, for many intact agricultural products such as fresh fruits.

Several recent studies used laser as a light source to generate scattering images or profiles on intact fruit, which were acquired using either a color CCD camera or a single-channel monochromatic CCD detector. Tu et al. (1995) conducted a preliminary study in which a He–Ne laser at 670 nm was used as a light source to study tomato and apple ripeness and firmness. They reported that the total number of pixels recorded by the red band CCD above a specified threshold value was related to the maturity stages of tomatoes and apple fruit firmness. McGlone et al. (1997) used a diode laser at 864 nm to study scattered light intensities from kiwifruit. Scattered light from the fruit was measured at different scattering angles or distances from the light incident point using a single-channel CCD detector. McGlone et al. (1997) reported that the intensity of light emitted from the fruit increased with decreasing firmness, especially at larger angles. A moderately good correlation between scattering measurements and firmness was obtained but the standard error was high, which led McGlone et al. (1997) to question the potential of the technique for online grading of kiwifruit. Although these reported studies are still preliminary in terms of measurement technique and algorithms development, they have generally shown that light scattering is related to the condition of fruit. As a light source, diode lasers are easy to implement and low in costs, but they only provide light scattering information at one spectral band (or wavelength), which is insufficient for predicting fruit quality. Multiple wavelengths and/or selected spectral regions may be needed in order to obtain more useful information about fruit firmness and SSC.

In this research, a multispectral imaging technique was investigated for measuring light scattering profiles from apple fruit at selected spectral bands in the near-infrared region between 680 and 1060 nm. Computer algorithms were developed to quantify the multispectral scattering images and relate them to fruit firmness and SSC.

2. Materials and methods

2.1. Fruit samples

‘Red Delicious’ apples were obtained from Michigan State University Clarksville Horticulture Experiment Station Orchard in Clarksville, MI and a commercial orchard in Michigan. These apples were stored in controlled atmosphere environment for about 5–6 months before they were used for this study. The apples were refrigerated in a walk-in cooler at 5 °C (or 40 °F) during the multispectral imaging study, which was carried out over a period of 4 weeks. Approximately 40 fruits were measured for a given test day. These test apples were placed at room temperature (24 °C) for at least 15 h before measurements were started. A total of 550 apples were tested for this study. The statistics of fruit firmness and Brix values (a measure of SSC) for all test apples are summarized in Table 1.

2.2. Wavelengths selection

Absorption and scattering are interrelated, and they influence each other. Although this study was to quantify light scattering profiles, it also indirectly measured light absorption at selected wavelengths. Our capability of predicting firmness and SSC would be improved by including those wavelengths that were found to be useful from NIRS studies. Literature review was conducted to select appropriate wavelengths for the multispectral imaging of apple fruit in the visible and short wave near-infrared region (Vis/SWNIR) between 400 and 1100 nm, which was covered by a CCD camera available to this research. It was found that wavelengths identified or used by previous studies are often different due to different measurement and data processing techniques and various conditions and origins of fruits used. For this research, five wavelengths were selected: 680, 880, 905, 940, and 1060 nm. The 680 nm wavelength was selected because it relates to the absorption of light by chlorophyll in fruit (Abbott et al., 1997). The actual wavelength for chlorophyll absorption may differ from various reported studies and the same is also true in discussion of the other four wavelengths. Chlorophyll content decreases as fruit become more mature or riper. This wavelength was found to be useful for predicting the firmness of apples (Moons et al., 1997; Tu et al., 1995) and the SSC of melons (Sugiyama, 1999). Wavelengths at 880 and 905 nm were used for predicting the SSC of fruits (Bellon et al., 1993; Guthrie and Walsh, 1999; Kouno et al., 1993; McGlone and Kawano, 1998; Moons et al., 1997; Peiris et al., 1998; Slaughter, 1995; Ventura et al., 1998). McGlone et al. (1997) used an 864 nm laser to measure light scattering in kiwifruit for firmness prediction. The 940 nm wavelength was useful for prediction of fruit firmness (Moons et al., 1997) and SSC (McGlone and Kawano, 1998; Ventura et al., 1998). The wavelength at 1060 nm was reported for predicting SSC (Moons et al., 1997). Choi et al. (1997) reported that the regions of 440–738 and 920–1058 nm were most useful for predicting apple fruit firmness.

Table 1
Statistics of the firmness (N) and soluble solids content (or SSC (%)) of Red Delicious apples used in the research

	Mean	STD	Minimum	Maximum
Firmness ($n = 550$)	57.3	11.5	34.2	84.5
SSC ($n = 550$)	13.0	1.2	9.7	16.5

2.3. System set-up

A multispectral imaging system was assembled for this research, which is shown schematically in Fig. 1. The system consisted of a high performance, air-cooled CCD camera (Model C4880-21, Hamamatsu Corporation, Japan) with a zoom lens (F2.5–16C and focal lengths of 18–108 mm), a neutral density filter (NDF) (Edmund Optics Inc., NJ, USA), a filter wheel containing five 50 mm bandpass filters (±10 nm, CVI Laser Corp., CA, USA) and a highly focused broadband light source. The light source was generated from a 250 W quartz tungsten halogen lamp with a dc control unit (Thermo Oriel, CT, USA). Light was passed through an optic fiber (600 μm in diameter and 0.22 numerical aperture) and lenses to form a sharp, focused beam at the fruit, which illuminated a portion of the fruit. After interacting with the fruit tissue, a portion of the light scattered back and exited from the fruit in an area (scattering area) contiguous and adjacent with the incidence area (Fig. 2).

Beam size was an important consideration in the system design. A larger beam offers greater light

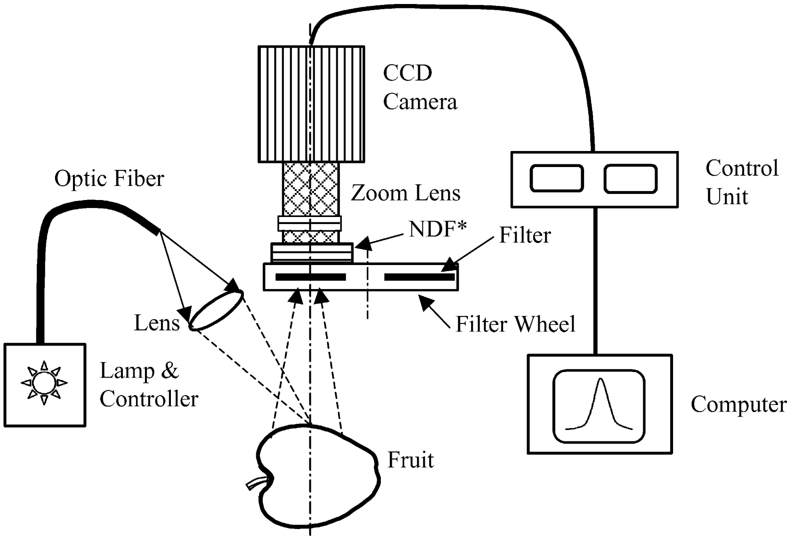

Fig. 1. Schematic of a multispectral imaging system for measuring light scattering profiles from apple fruit.

throughput but it could complicate quantification of light scattering in the fruit because the photons exiting from the same location of the fruit do not necessarily have the same pathlengths. A smaller beam is desirable for quantification of light scattering but it also means a lower efficiency for the lighting system, fewer photons received by the detecting device, and a smaller scattering area. After careful consideration of these factors, the beam size was selected to be 0.8 mm in diameter with a divergent angle of 0.032 radians. With this beam size, we were able to obtain good signals from a scattering area of 25 mm diameter (Fig. 2).

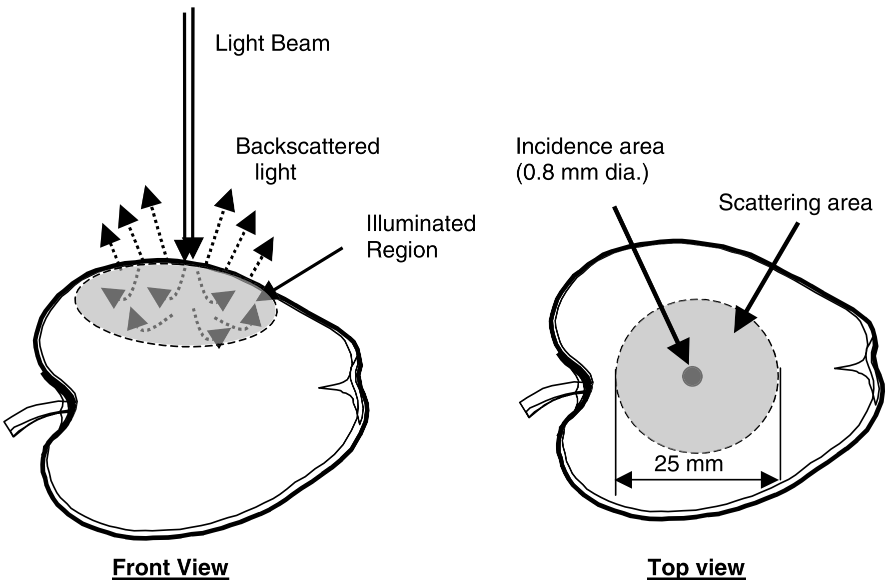

Fig. 2. Concept of measuring scattering images from an apple fruit for predicting fruit firmness and soluble solids content.

The incident angle of the light beam was set at 21°. At this angle, specular or surface reflectance would not be acquired by the imaging system. The distance from the filter wheel to the fruit sample was 210 mm. The pixel resolution was 0.065 mm per pixel.

The neutral density filter used in this research had variable transmission efficiencies in the radial direction with the lowest transmission at the center. This filter was used to reduce the intensity of light reflected from the beam incident area that could easily saturate a large number of CCD pixels. Without the NDF, the beam intensity would have to be reduced to avoid and/or reduce pixel saturations and the useful light scattering area would be considerably smaller.

2.4. Experimental procedure

One location around the equator of the fruit was selected for multispectral imaging (Fig. 2). Fruit were placed on a sample holder with the stem end-calyx axis horizontally. During acquisition, each of the five filters was rotated in sequence to obtain five spectral images. The exposure time was set at 1.0 s for the first four filters and a longer exposure time (5.0 s) was used for the last filter (1060 nm) because of a lower photon efficiency of the camera at this wavelength. For each filter, four images were taken from each fruit and averaged to improve the signal-to-noise ratio.

After completing the imaging of test apples, fruit firmness and SSC were measured using the standard destructive methods from the same location where scattering measurements had been taken. Magness–Taylor (MT) penetration measurements were performed with a TA.XT 2 Texture Analyzer (Stable Micro Systems, Goldalming, Surrey, UK) at a loading rate of 2 mm/s. A small portion of fruit skin was first removed from the fruit and an 11 mm MT probe was penetrated into the fruit tissue for a distance of 9 mm. The maximum force was recorded as a measure of fruit firmness. Immediately after MT measurements, juice was extracted and its Brix value was measured using a digital refractometer (Model PR-101, Atago Co. Ltd., Japan).

2.5. Image processing algorithms

Fig. 3 is a flowchart diagram showing the procedures to process multispectral scattering images for predicting fruit firmness and SSC. The multispectral images of apple fruit were first corrected using the transmission efficiency image from the NDF to obtain the scattering profile images that would be obtained without the NDF. The NDF transmission efficiency image was obtained by comparing the images acquired from a standard reflectance panel (Labsphere Inc., MA) with and without the NDF under the same illumination of a quartz tungsten halogen lamp. Next, the center of scattering images was determined by comparing the average pixel value calculated from a 3×3 pixel moving window in the central image region of 50×50 pixels from the spectral image at 1060 nm. The image center was defined as the location that corresponds to the maximum light intensity. This center varied within ±10 pixels with the test fruit due to the

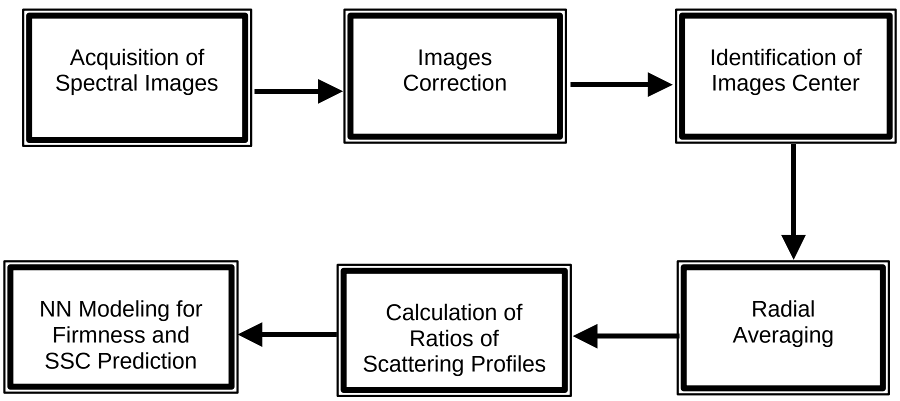

Fig. 3. Flowchart diagram on the procedures of acquiring and processing multispectral images for predicting apple fruit firmness and soluble solids content (SSC).

variability of apple fruit in size and surface geometry. The wavelength at 1060 nm was used for identifying the image center because no saturation was observed at this wavelength for all fruit samples. Upon identification of the image center, radial averaging was performed to obtain the average value of all pixels within each circular band of a specified width (or pixels). For this study, each circular band for radial averaging was seven pixels wide or 0.48 mm. The scattering images were divided into 26 equal width rings, including the center circle of 0.48 mm in radius, encompassing a 25 mm diameter scattering region from the test fruit. The averaging process effectively reduced scattering profiles from two- to one-dimensional and, at the same time, it greatly improved the signal-to-noise ratio.

Different approaches could be used to analyze scattering profile data to predict fruit firmness and SSC. McGlone et al. (1997) used a two-parameter phenomenological model to fit the scattering profiles from kiwifruit and then performed linear regressions to relate model parameters to fruit firmness. This approach is straightforward and may be simpler in interpreting the results. But the curve fitting process can be time consuming and less effective because the model may not fit the scattering profile accurately due to steep light intensity changes close to the incidence area (Fig. 4). In this study, a backpropagation neural network with one hidden layer and a sigmoid transfer function was used to predict fruit firmness and SSC.

Two methods may be used to preprocess the scattering image profile data before they were input into the NN. In the first method, principal component analysis (PCA) or partial least square regression (PLS), which is widely used in the chemometric analysis of near-infrared spectral data, could be used to extract principal component scores, and they would then be used as inputs to the NN. The advantages of this method include reduced dimensionality of input data, removal of some noise from the original data, and a reduced chance of overfitting the training data. The second method simply uses all scattering profile data points as inputs to the NN. Since each scattering profile only contained 23 useful data points after radial averaging, the size of inputs was not a problem for this study. Hence, the second method was chosen for this study.

After extensive testing of the NN, it was found that optimal results were obtained when the NN had neurons of 10 and epochs of 20. A computer program was written using the Matlab Neural Network Toolbox (Version 4, The MathWorks Inc., MA, USA) to implement the neural network.

Several forms of NN inputs were considered, including individual scattering profiles, differences between two scattering profiles, and ratio of two scattering profiles. Ratios of scattering profiles from two different spectral bands gave the best and most consistent predictions in both firmness and SSC. Hence, in the following discussion, only the results from ratios of scattering profiles are presented. A search procedure was implemented to find the best ratio combinations for predicting fruit firmness and SSC. It first found the single best ratio of two scattering profiles for predicting fruit firmness and SSC. A second ratio was then added to determine if this addition would improve the model performance. Once the best two ratio combinations were found, the procedure was repeated to determine if a third ratio combination was needed until no further improvement was obtained.

The neural network was trained using 3/4 of the data (412 apples) and validations were performed using the remaining samples (138 apples).

3. Results and discussion

3.1. Scattering profiles

Fig. 4 shows light scattering profiles between 1.5 and 12.5 mm from 138 Red Delicious apples, which were used in the NN validation, for the five wavelengths after corrections with the NDF. The scattering profiles in the central region within 1.5 mm were not included because they were not used in the data processing for the reason explained later. Due to the absorption of light by chlorophyll, scattered light intensities at 680 nm were considerably lower than those at 880 and 905 nm. Highest scattered light intensities were observed at 880 and 905 nm. At 940 nm, the recorded intensities were lower than those at 880 and 905 nm. The intensities at 1060 nm were significantly lower than those at the other four wavelengths. It should be mentioned that the intensity profiles shown in Fig. 4 have not been corrected for variable spectral response efficiencies (or photon conversion efficiencies) of the CCD for different wavelengths and

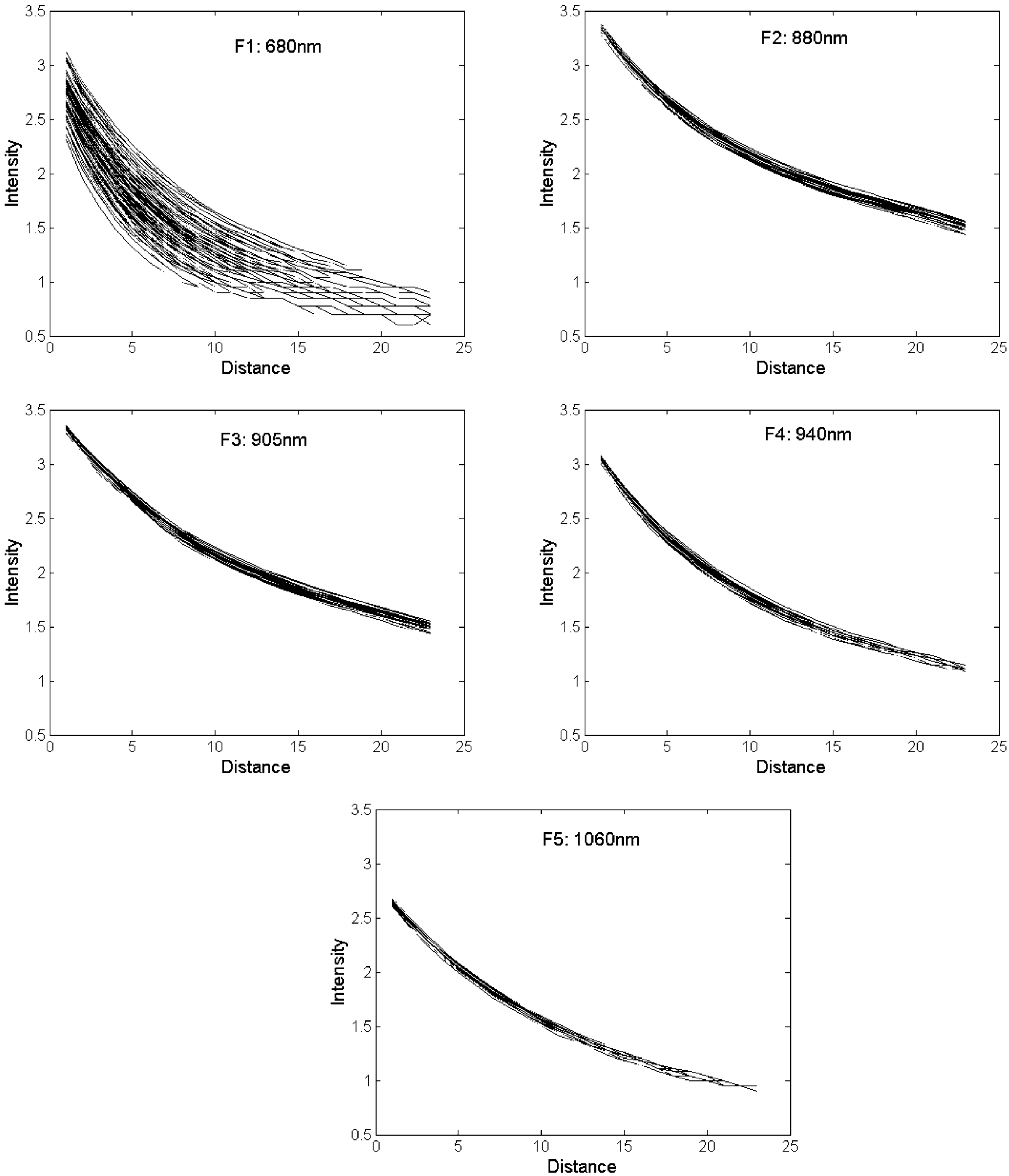

Fig. 4. Log scale light scattering profiles over the radial distances between 1.5 and 12.5 mm for Red Delicious apples at five spectral bands after radial averaging of two-dimensional scattering images.

hence they do not reflect the actual amount of photons emitting from the fruit. The CCD camera used in this research had the peak spectral response greater than 90% around 650 nm, and its spectral response dropped to about 50–60% at 900 nm and was less than 15% at 1060 nm.

The light intensity was the greatest in the center (not shown in Fig. 4) and decreased drastically as the distance increased. An examination of all scattering profiles showed that within a radial distance of 1.5 mm from the image center, intensity profiles at different wavelengths did not show a consistent pattern and some crossovers were observed among the scattering profiles. This indicates that the signal within and immediately adjacent to the beam incident area of 0.8 mm diameter was not stable and consistent. Beyond this central region, the intensity profiles became more consistent and few crossovers were observed (Fig. 4). It was further confirmed that when the entire scattering profiles covering the radial distance between 0.0 and 12.5 mm were used, prediction results were poor. The best prediction results were obtained by excluding the data within the 1.5 mm distance. Hence, the following discussion is confined to the results obtained using the intensity profiles between 1.5 and 12.5 mm, each of which was represented by 23 data points.

Table 2
Comparison of the best ratio combinations for firmness predictions of Red Delicious apples[a]

Number	Ratio combinations[b]	Calibration[c] (r/SEC)	Validation[d] (r/SEP)
1	F1/F4	0.83/6.4	0.84/6.3
2	F1/F4, F3/F4	0.87/5.7	0.86/5.9
3	F1/F4, F2/F3, F3/F4	0.88/5.4	0.87/5.8

[a] There were a total of 550 apple fruits used in the study; 412 fruits were used for neural network training and 138 fruits for validation.
[b] F1, F2, F3, F4, and F5 correspond to the five filters at 680, 880, 905, 940, and 1060 nm, respectively.
[c] SEC: standard error of calibration in Newton.
[d] SEP: standard error of prediction in Newton.

3.2. Firmness predictions

Table 2 summarizes the best ratio combinations for predicting apple fruit firmness when only one, two, or three ratios were used in the NN. The F1/F4 ratio, where F1 and F4 represent, respectively, the

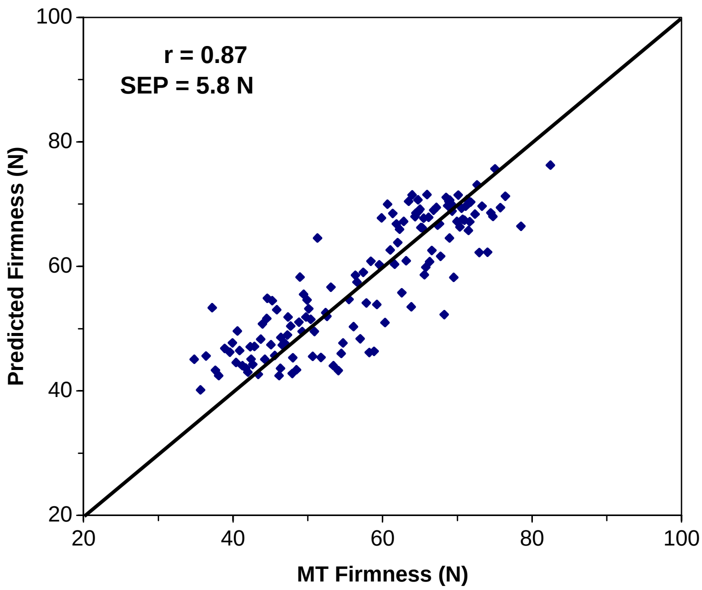

Fig. 5. Predicted firmness values obtained from a backpropagation neutral network with one hidden layer and inputs of three scattering profile ratio combinations (F1/F4, F2/F3, F3/F4) vs. Magness–Taylor (MT) firmness measurements for Red Delicious apples. The bandpass filters used are: F1 = 680, F2 = 880, F3 = 905, and F4 = 940 nm. Each filter had a bandpass of ±10 nm.

scattering profiles from the 10 nm spectral bands centered at 680 and 940 nm, gave the best firmness predictions when only one ratio was used; the correlation of prediction was 0.83 and the standard error of prediction (SEP) was 6.3 N. The two best ratio combinations were given by F1/F4 and F3/F4 with $r = 0.86$ and SEP $= 5.9$ N. With three ratio combinations (F1/F4, F2/F3, and F3/F4), the correlation of prediction was 0.87 and the SEP was 5.8 N. Inclusion of additional ratio combinations in the NN did not improve the model performance. These results indicate that the three ratio combinations with four spectral bands gave the best predictions of apple firmness (Fig. 5). The two ratio combinations may also be useful because only three spectral bands are required for the system.

Table 2 also shows that the differences between NN training and validation results are quite small, as measured by r and standard error of calibration (SEC; for training) or SEP. This indicates that the NN was robust and not over trained. A larger difference between the training and validation is often indicative of a less robust and possibly over trained NN.

The firmness predictions obtained from this research compare favorably with those reported in previous studies using near-infrared spectroscopy or laser imaging techniques. Moons et al. (1997) applied NIRS in the spectral region between 400 and 1700 nm to predict apple fruit firmness and reported an r-value of 0.80 and a SEP of 7.2 N. Lu et al. (2000) reported that NIRS was not good enough for predicting apple firmness, with $r = 0.48$ and SEP $= 8.6$ N. Choi et al. (1997) reported an r-value of 0.70 and a SEP of 7.0 N for Red Delicious apples. Clearly, the results from this research are encouraging, indicating the potential of using multispectral scattering profiles for predicting apple fruit firmness.

3.3. SSC predictions

The single ratio combination, F3/F4, was able to predict SSCs with the correlation coefficient of 0.72 and the SEP of 0.84%. The best two ratio combinations were F2/F3 and F3/F4, which gave a correlation coefficient of 0.77 and the SEP of 0.78% (Fig. 6). Inclusion of additional ratio combinations did not result in improved SSC predictions. The SSC predictions obtained from this study are respectable, though they are not as good as those reported in some NIRS

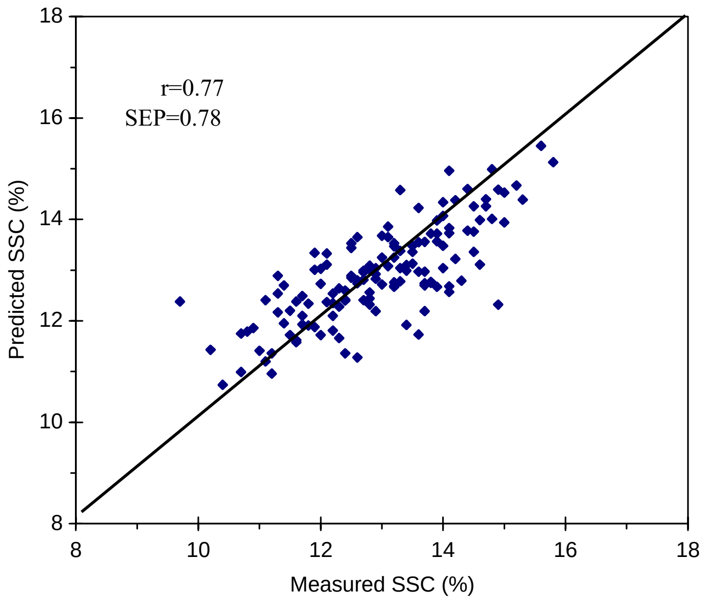

Fig. 6. Predicted soluble solids contents (SSC) for Red Delicious apples using a backpropagation neutral network with inputs of two ratio combinations of F2/F3 and F3/F4 vs. the values measured from the Brix refractometer. F2, F3 and F4 correspond to 880, 905, and 940 nm, respectively.

studies. Several studies (Choi et al., 1997; Lu et al., 2000; Moons et al., 1997) have shown that NIRS can predict fruit SSCs with the SEP less than 0.5% and the *r*-value being 0.9 or higher. Choi et al. (1997) and Moons et al. (1997) used the spectral regions of 400–2500 and 400–1700 nm, respectively, whereas Lu et al. (2000) used the region of 800–1700 nm. Relatively poor SSC predictions from this study are not totally surprising in view of the fact that only three wavelengths were used for predicting apple fruit SSC. The technique proposed in this study was primarily used to quantify light scattering in apples. Hence, the data acquired from apple fruit were expected to be more useful for predicting fruit firmness than SSC.

In this study, apple samples harvested from two orchards were tested over a period of 4 weeks. It is not clear how light scattering characteristics were affected by this sample conditioning procedure. There is a need to test a wide range of apple samples from different orchards and with different post-harvest conditions to determine how these factors will affect light scattering characteristics and prediction results. The present system can only acquire one image at a time, which is slow and inefficient. For future online applications, an imaging system that can acquire all spectral images simultaneously is required, and such technology is currently available. Improvement in light source (i.e. more powerful light source and more efficient light delivery design) is also critical for faster acquisition of scattering images. Further research is being conducted in our laboratory to develop a more efficient and effective multispectral imaging system for rapid acquisition of scattering images to meet the online sorting speed requirement.

4. Conclusions

Light scattering from apple fruit at selected near-infrared wavelengths is useful for predicting fruit firmness and soluble solids content. The backpropagation neural network with inputs of ratios of scattering profiles was effective for predicting fruit firmness and soluble solids content. The three ratio combinations with four wavelengths at 680, 880, 905, and 940 nm gave the best predictions of apple fruit firmness with the correlation coefficient of 0.87 and the standard error of prediction of 5.8 N. For soluble solids predictions, only two ratios combinations were needed, which included three wavelengths at 880, 905 and 940 nm.

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